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Review Article

Towards effective and integrated riparian wetland monitoring in Europe: challenges and opportunities

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Abstract

Riparian Wetland conservation and restoration in Europe increasingly rely on nature-based solutions, yet biodiversity monitoring of their implementation remains fragmented across scales, methods and policy frameworks. This paper synthesises current approaches in wetland monitoring and proposes an integrated, adaptive framework linking long-term, system-orientated observation with short- to medium-term, intervention-focused restoration monitoring. Combining site-based surveys with standardised, multi-scale assessments enables differentiation of natural variability from human pressures, detection of tipping points in species sensitivity to climate pressures and evaluation of restoration outcomes under EU policies, such as the WFD, the Habitats and Birds Directives and the Nature Restoration Regulation. Besides conventional biodiversity monitoring, we highlight innovations that address critical monitoring gaps: artificial intelligence–supported remote sensing using satellites and unmanned aerial vehicles, sensor networks for near-real-time hydrological observations, environmental DNA metabarcoding and citizen-science approaches. Essential biodiversity variables and essential ecosystem-service variables are emphasised as integrative indicators that connect ecological integrity, ecosystem functioning and human well-being. Finally, we outline the enabling conditions for a harmonised European wetland monitoring architecture, supported by major environmental research infrastructures that provide long-term ecological data, advanced digital tools and integrated assessments essential for evidence-based, climate-resilient restoration.

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Highlights

- Riparian wetland conservation and restoration in Europe increasingly use nature-based solutions, but biodiversity monitoring remains fragmented across scales, methods and policies.
- Standardised, multi-scale assessments combined with site-based surveys help distinguish natural variability from human pressures.
- Integrated monitoring supports early detection of tipping points in species responses to climate change.
- Innovative monitoring tools are highlighted, including AI-supported remote sensing (satellites and UAVs), sensor networks, eDNA metabarcoding and citizen science.
- Major environmental research infrastructures are identified as key supports for long-term data, digital tools and evidence-based, climate-resilient restoration.
- The approach enables evaluation of restoration outcomes under key EU policies (WFD, Habitats and Birds Directives, Nature Restoration Regulation).

Key words: Citizen science, eDNA, evaluation tools, remote sensing, restoration, restoration success, riverine floodplains, wetland ecosystem observation

Importance of riparian wetland monitoring

Despite major advances, biodiversity monitoring in European wetlands remains fragmented, constrained by data gaps, methodological inconsistencies and the inherent complexity of systems that are both spatially heterogeneous and temporally dynamic (Hielkema et al. 2023; Moersberger et al. 2024). Given their ecological importance and societal value, but also current status (see Kaden et al. 2026), wetlands demand adaptive, multi-scale monitoring frameworks that integrate short- and long-term perspectives and explicitly link biodiversity, ecosystem functions and restoration outcomes. Consistent, long-term monitoring of riparian wetlands is essential for detecting ecological change, understanding the processes that sustain biodiversity and the ecosystem services these systems provide and assessing their resilience to environmental and human-induced pressures. It focuses on detecting trends in hydrology, vegetation and fauna; distinguishing natural variability from anthropogenic pressures; and assessing progress towards achieving good ecological status and favourable conservation status under European legislation such as the Water Framework Directive (WFD) and the Habitats and Birds Directives (Council of the European Communities 2000; European Commission 1992, 2009). Long-term wetland monitoring is, therefore, essential for evaluating ecosystem trajectories, identifying climate-driven changes and providing the baseline conditions necessary for designing effective restoration strategies (Gillson et al. 2021). In contrast, wetland restoration monitoring assesses the effects of specific interventions, including hydrological reconnection, sediment re-activation and vegetation re-establishment and generally operates over shorter, management-relevant time frames. It assesses whether interventions achieve their intended ecological and functional improvements, including enhanced biodiversity, restored hydrological regimes and improved provision of ecosystem services, such as nutrient retention and flood regulation (Stammel et al. 2012; England et al. 2021; Schulz-Zunkel et al. 2022). Restoration monitoring thus provides feedback that

provides information for adaptive management and helps optimise restoration design and implementation in real time. Compared to long-term monitoring, which reveals gradual ecological trends, short-term monitoring provides rapid feedback on immediate management actions and system responses. Integrating both temporal dimensions allows managers to identify early indicators of success or failure, refine restoration measures and assess whether observed changes persist and scale-up over time (Pereira and Cooper 2006; Khatik 2022). When combined, wetland monitoring (long-term, system-orientated) and restoration monitoring (short-term, intervention-orientated) form a coherent, evidence-based framework that connects ecological observations with management decisions. This integration ensures that conservation and restoration measures are effective not only at individual sites, but also aligned with wider policy objectives under the Nature Restoration Regulation, the EU Biodiversity Strategy for 2030 and relevant climate and water frameworks. Together, long-term ecological monitoring and short-term adaptive responses create a robust, science-based foundation for wetland management and restoration across Europe. Building on these considerations, the ecological status assessment of floodplain wetland ecosystems has gained increasing importance (Dziock et al. 2006; Scholz et al. 2009; Erős et al. 2019; Kaden et al. 2023; Mohanty et al. 2024). Such assessments serve three primary functions:

1. Tracking policy progress – as indicators of success towards biodiversity protection and degradation prevention under EU and international commitments;
2. Guiding action – by identifying where conservation, restoration or climate-adaptation interventions are most needed; and
3. Evaluating effectiveness – by comparing outcomes of past and present measures to provide information for adaptive management and future policy refinement.

Integrating these monitoring dimensions — spatial, temporal and functional — within a unified assessment framework will be crucial for ensuring that wetland conservation and restoration efforts effectively contribute to Europe's biodiversity, climate and water-management objectives.

Policy goals – opportunities and needs

The conservation and restoration of habitats and species are guided globally by the Kunming–Montreal Global Biodiversity Framework (CBD 2022), which identifies biodiversity monitoring as a cornerstone for evaluating progress towards restoration and protection targets (Perino et al. 2022). In Europe, three main policy frameworks govern biodiversity conservation and restoration: the Bern Convention of the Council of Europe, the EU Habitats and Birds Directives and the EU Nature Restoration Regulation. The Bern Convention (Council of Europe 1979) promotes international cooperation across the pan-European region to protect endangered and vulnerable species and habitats. In contrast, the EU Habitats Directive (Council Directive 92/43/EEC) establishes binding legal obligations within the European Union, requiring Member States to designate Special Areas of Conservation (SACs) for priority habitats and species. The Birds

Directive (EU 2009/) complements this by safeguarding all wild bird species naturally occurring in the EU through the establishment of Special Protection Areas (SPAs). Together, these Directives form the Natura 2000 network — the most extensive coordinated network of protected areas in the world. The recently adopted Nature Restoration Regulation (European Parliament and Council 2024) extends the scope of biodiversity policy beyond protection by setting legally binding targets for restoring degraded ecosystems, including all types of wetlands. It calls for measurable improvements in biodiversity and ecosystem functionality and introduces requirements for consistent, harmonised monitoring and reporting. The Water Framework Directive (WFD; Council of the European Communities 2000) complements these conservation frameworks by addressing the ecological status of surface and groundwater bodies that often include or influence wetland and riparian habitats. Although not designed specifically for biodiversity conservation, its biological, physicochemical and hydromorphological indicators provide valuable data for assessing wetland condition and evaluating restoration outcomes. Together, these policy instruments form a framework for the protection and management of wetland ecosystems in Europe, whose full potential can only be realised if implemented consistently across the entire continent, not only within the European Union. The major challenge lies in mainstreaming biodiversity objectives across related policy domains, particularly agriculture, water management, climate adaptation and spatial planning, to ensure that conservation, restoration and monitoring actions are coherent and mutually reinforcing. Strengthening policy coherence would enhance data integration, improve resource allocation and enable a more systematic evaluation of progress towards European restoration and biodiversity targets. As biodiversity monitoring connects these policy commitments to measurable ecological outcomes, developing harmonised and long-term monitoring frameworks is essential for evaluating the effectiveness of restoration efforts. The following section examines the current state of riparian wetland biodiversity monitoring in Europe, highlighting opportunities for improved data integration, methodological innovation and cross-sectoral coordination.

Ecological status assessment of riparian wetlands – challenges and ways forward

Building on the policy frameworks outlined above, effective conservation and restoration of riparian wetlands require robust and integrated ecological status assessments that also capture their contribution to human well-being. Understanding the functioning of river–floodplain systems is central to this task. The Flood Pulse Concept remains a foundational model describing how periodic inundation connects rivers with adjacent floodplains, regulating water, nutrient and sediment exchanges that sustain habitat diversity, productivity and ecological integrity (Junk et al. 1989; Tockner et al. 2000). These hydrological dynamics underpin not only biodiversity, but also the delivery of vital ecosystem services, including water purification, flood regulation, carbon sequestration and recreation, which directly support local and regional communities. Consequently, ecological assessment and restoration must adopt a landscape-scale perspective that integrates hydrological connectivity, morphodynamics and ecosystem service flows (Tockner et al. 2000; Åhlén et al. 2022). Within the

EU, the Water Framework Directive (WFD) provides the primary framework for assessing the ecological status of aquatic ecosystems, based on biological, hydromorphological and physicochemical quality elements reported every six years by Member States. While the WFD has led to measurable improvements in water quality and habitat conditions (Zacharias et al. 2020), freshwater biodiversity in Europe continues to stagnate or decline (van Rees et al. 2020; Haase et al. 2023). Furthermore, current monitoring approaches rely on a limited set of biological quality elements and indicator species, often emphasising regulatory compliance over functional ecosystem recovery (Rouillard et al. 2018). As a result, many ecosystem services provided by wetlands remain undervalued or insufficiently integrated into management decisions and nature conservation management plans (Hielkema et al. 2023). Riparian wetlands include numerous priority habitats listed in Annex I of the Habitats Directive, which require specific conservation and restoration measures (Januschke et al. 2023). However, effective ecological assessment should move beyond the evaluation of individual species or habitats to encompass ecological integrity, the capacity of ecosystems to maintain structure, function and service provision under changing environmental and socio-economic conditions (Dziock et al. 2006; Henle et al. 2006; De Berry et al. 2015). This requires assessing hydrological and geomorphological processes, anthropogenic pressures and the spatial and temporal variability that shape ecosystem dynamics (Erős et al. 2019; Schulz-Zunkel et al. 2022). Modern approaches increasingly link biodiversity indicators with ecosystem service metrics, using frameworks, such as Essential Biodiversity Variables (EBVs) and Ecosystem Integrity Indicators to connect species-based data with ecosystem functions and benefits. Harmonised workflows integrating *in situ* monitoring, remote sensing and modelling enable assessments of both ecological condition and service provision across scales (Lumbierres et al. 2025). Such integrative methods align with the European biodiversity monitoring architecture and support evaluation of progress under the Nature Restoration Regulation. A further challenge arises from the intense competition between land and water uses in large river systems, where navigation, flood control, hydropower, agriculture and settlement interests co-exist. In such contexts, restoring fully natural floodplains is rarely feasible. Instead, a process-based and multifunctional restoration approach offers a realistic pathway, prioritising the recovery of key ecological processes (e.g. lateral connectivity, sediment dynamics, natural vegetation succession), while balancing economic and social needs (Dufour and Piégay 2009; Perino et al. 2019). Embedding these principles into assessment frameworks allows for evaluating both ecological integrity and the capacity of river–floodplain systems to deliver ecosystem services sustainably under competing land-use pressures.

Monitoring the effectiveness of restoration measures

Monitoring the effectiveness of restoration measures is essential for adaptive floodplain management, enabling practitioners to learn from early outcomes and adjust interventions accordingly. Yet, post-restoration evaluation is still rarely included in wetland restoration guidelines across Europe (Santaoja et al. 2025). Monitoring is crucial for assessing measures, such as optimising discharge, modifying land use, implementing structural interventions or expanding

protected areas. Abiotic parameters, including habitat structure, water chemistry and hydromorphology, can be used immediately to refine management practices, whereas biological responses often occur with time lags and reflect cumulative anthropogenic or climatic impacts (Schulz-Zunkel et al. 2022). Comprehensive monitoring, therefore, requires the inclusion of multiple taxonomic and functional groups, whose responses differ depending on the intervention type (Scholz et al. 2009; Müller et al. 2016; Januschke et al. 2017; Januschke et al. 2023; Wenskus et al. 2025). Biological monitoring should be complemented by assessments of hydrological and morphodynamic processes (Thoms 2003). Spatially, monitoring needs to encompass multiple scales, from small plots (e.g. 1 m^2) to entire river sections, to adequately capture spatial and temporal heterogeneity (del Tánago et al. 2016; Staentzel et al. 2018). Finally, investigating local assessments of climate change in relation to extreme heat stress, drought and precipitation requires data monitoring compiled from scientific sources (Zscheischler et al. 2018). Extreme events should be recorded through long-term programmes complemented by targeted event-based assessments (Stammel et al. 2021). The inherently dynamic character of riparian wetland ecosystems makes it difficult to define fixed monitoring intervals; hence, biological communities and sensitive indicator species are valuable integrators of short-term disturbances and long-term ecological trends (Dziock et al. 2006).

Although restoration programmes in rivers and floodplains are expanding across Europe, systematic evaluation of restoration outcomes remains limited (England et al. 2021). Policy-driven assessments under the Water Framework Directive and the Birds and Habitats Directives focus on selected organism groups and, therefore, capture only a fraction of floodplain biodiversity. This gap has prompted the development of more comprehensive, standardised monitoring tools. One example is the BioAu-Tool (Januschke et al. 2023), a stakeholder co-designed, multi-taxon method for assessing restoration success in riverbanks and floodplain systems (Fig. 1). The tool evaluates outcomes across vascular plants, terrestrial and aquatic molluscs, ground beetles, amphibians and birds, integrating species and habitat indicators across 18 floodplain types in Central Europe. It provides two assessment levels: habitat screening and detailed species analysis; and supports before–and–after or space-for-time comparisons. Practitioner resources include methodological guidelines, indicator species lists, semi-automated Excel scoring tools and abiotic habitat fact sheets. As such, the BioAu-Tool offers a rigorous, scalable framework that links restoration measures to measurable ecological responses and is currently being tested nationwide for efficiency and user-friendliness.

Methods such as spatial mapping and transect-based surveys are effective in capturing unexpected developments and structural changes. Initially, higher monitoring frequency is recommended, which can gradually decrease once the restoration trajectory and system variability become well understood (Lang et al. 2013). This paper, therefore, reviews the current state of riparian wetland biodiversity monitoring in Europe, emphasising the integration of site-specific and long-term approaches. It identifies key challenges in data management, standardisation and biodiversity vulnerability assessment and explores innovative solutions, such as remote sensing, artificial intelligence and citizen science. Finally, it discusses the inclusion of climate data and EU policy standards to guide the development of more effective, evidence-based monitoring frameworks for wetland restoration in a changing climate.

Figure 1. Implementing the BioAu tool - biocoenotic method to control the success of restoration measures in floodplains (Photos: K. Januschke, K. Groh and M. Scholz).

Effective conservation and restoration of riparian wetlands require a comprehensive understanding of ecological processes, human-induced drivers and governance mechanisms. Implementation of nature conservation plans highlights the urgent need for wetlands to effectively incorporate climate adaptation strategies, ensuring resilience under future climate change conditions (Hielkema et al. 2023). Floodplain ecosystems are influenced by interactions between hydrology, geomorphology and biological communities, but also by land-use dynamics, institutional responsibilities and societal priorities. Traditional monitoring frameworks have focused primarily on biophysical indicators — particularly biodiversity and water quality — while paying less attention to the socio-economic and policy contexts that determine restoration success. As Europe transitions towards multifunctional landscapes and measurable restoration targets, developing integrated monitoring frameworks that connect ecological, hydrological, functional and governance dimensions has become a key priority.

Monitoring and evaluation of riparian wetland habitats

While the evaluation of aquatic habitats in rivers is well established, standardised approaches for floodplain habitats remain underdeveloped (Foeckler et al. 1991; Henle et al. 2006; Dziock et al. 2006; Ilg et al. 2008; Gerisch et al. 2012). The absence of harmonised assessment criteria limits comparability across Member States, even though the composition, structure and functional quality of habitats are central indicators of ecological integrity and ecosystem-service provision, including nutrient retention, flood regulation and carbon storage (Burkhard et al. 2012). Most existing monitoring frameworks rely on localised field data, which provide detailed insights, but is often difficult to upscale. In contrast, remote-sensing tools and harmonised European datasets, such as CORINE Land Cover and EUNIS, enable cross-border habitat mapping (Davies et al. 2004; Weiers et al.

2004; Lengyel et al. 2008). However, data accuracy and temporal resolution vary across regions, particularly in dynamic floodplain mosaics shaped by local hydrology and management practices (Koenzen 2005; Globevnik et al. 2021; Koenzen et al. 2021; Januschke et al. 2023). Recent European initiatives have, therefore, aimed to establish multi-criteria assessment systems that connect habitat quality, ecosystem functionality and management performance. The River Ecosystem Service Index (RESI) is a notable example, evaluating habitat provision as one of 18 ecosystem services using a five-point scoring system and 1-km river–floodplain segments (Brunotte et al. 2009; Pusch 2016; Fischer-Bedtke et al. 2020). Adapted to the Danube region (Stäps et al. 2022), RESI represents a model for integrating ecological and functional indicators within a policy-relevant spatial framework. Beyond RESI, several European projects and infrastructures are advancing integrated wetland monitoring by linking ecological and hydrological assessments with socio-economic and governance dimensions (Wantzen et al. 2026; Stammel et al. 2026). These initiatives (Table 1) collectively represent the building blocks for a coherent European monitoring architecture.

Integrating ecological, functional and governance dimensions

The initiatives in Table 1 show that progress towards integration is advancing across Europe, but remains fragmented and project based. Most efforts focus on specific ecosystems, scales or policy instruments, leading to overlapping, but disconnected datasets and indicators. A truly integrated framework should connect these components through shared standards, interoperable databases and coordinated governance mechanisms. Ecological indicators (e.g. species composition, habitat condition, hydromorphology) need to be complemented by functional measures (e.g. nutrient cycling, carbon balance, hydrological connectivity) and governance indicators (e.g. management effectiveness, stakeholder participation, policy coherence). Monitoring frameworks must, thus, evolve from describing the state of ecosystems to understanding the drivers, pressures and enabling conditions that determine their resilience and restoration success (Perino et al. 2022). Integration also requires addressing how data provide information for decision-making. Projects like Restore4Life, SELINA and Biodiversa+ explicitly focus on linking monitoring with science–policy interfaces, ensuring that data on wetland condition and ecosystem services feed directly into policy processes, such as the Nature Restoration Regulation, Water Framework Directive,and EU Biodiversity Strategy 2030. In the European Union, governance-orientated monitoring is shaped by policy objectives and legal requirements that guide how decisions are made and implemented. Effective adaptive management depends not only on ecological indicators and trends, but also on metrics that show how well institutions coordinate, how secure long-term funding is and how actively the public is involved. This ensures that ecological data are fully connected to the social and policy realities of restoration.

Future wetland monitoring must also be adaptive, scalable and interoperable. Combining long-term in-situ data (e.g. eLTER, DANUBIUS-RI) with Earth-observation datasets, ecosystem-service models and governance indicators will provide the multi-dimensional evidence base needed to assess restoration outcomes and resilience (Ohnemus et al. 2024; Stănica et al. 2025). Achieving interoperability between European research infrastructures and

Table 1. European initiatives and projects contributing to the development of integrated wetland monitoring frameworks.

Initiative / Project	Primary focus	Main monitoring dimensions	Spatial scale	Contribution toward an integrated framework	References / Links
RESI – River Ecosystem Service Index	Ecosystem-service assessment for river–floodplain systems	Ecological, hydromorphological, functional	National (Germany) / Regional (Danube adaptation)	Provides standardised multi-criteria approach linking habitat quality, ecosystem functions, and service delivery	Fischer-Bedtke et al. (2020); Pusch (2016); Stäps et al. (2022); Stammel et al. 2026
SWOS – Satellite-based Wetland Observation Service	Sentinel-based monitoring of wetland extent and condition	Remote sensing, hydrological, ecological	Pan-European / Global	Developed operational indicators for wetland monitoring using Copernicus data; model for scalable observation services	SWOS Consortium (2018) https://www.swos-service.eu/)
ALFAwetlands & WET HORIZONS	Mapping and restoration knowledge base for European wetlands	Ecological, spatial, functional	Pan-European	Produced the European Wetland Map and harmonised typologies; provides spatial foundation for cross-country monitoring	ALFAwetlands Consortium (2024) https://alfawetlands.eu/alfawetlands-press-release-2024/
REWET – Wetlands Restoration to Tackle Climate Change	Restoration monitoring focused on climate mitigation and ecosystem services	Ecological, functional, socio-economic	Transnational (EU case studies)	Integrates biodiversity, carbon, and hydrology indicators; demonstrates restoration–climate co-benefits	REWET HE Project (2024) https://www.rewet-he.eu/
Restore4Life	Decision-support system for wetland reconstruction and adaptive management	Ecological, hydrological, socio-economic, governance	Pan-European	Builds interoperable data platform integrating Copernicus, in-situ, citizen-science and socio-economic layers	Restore4Life Consortium (2024) https://restore4life.eu/
SELINA – Science for Evidence-based and Sustainable Decisions about Natural Capital	Mainstreaming ecosystem services and natural capital into decision-making	Governance, policy coherence, ecosystem-service integration	Pan-European / National hubs	Strengthens science–policy interfaces; aligns biodiversity monitoring with ecosystem-service and natural-capital accounting frameworks	SELINA Consortium (2024) https://project-selina.eu/
Biodiversa+ Monitoring & Governance Programme	Transnational coordination of biodiversity monitoring and governance evaluation	Governance, data interoperability, policy alignment	EU-wide	Advances harmonised protocols, data sharing and governance metrics across ecosystems	Biodiversa+ (2023) https://www.biodiversa.eu/biodiversity-monitoring/governance/
LIFE Programme (EU)	EU funding instrument for environment, nature and climate action	Institutional, financial, policy support	EU-wide	Provides financial and institutional backbone for wetland monitoring and restoration pilots	European Commission, LIFE Programme (2024) https://cinea.ec.europa.eu/programmes/life_en
eLTER & DANUBIUS-RI	Long-term ecosystem and river–sea system observation infrastructures	Ecological, hydrological, biogeochemical	Pan-European / Global	Ensures standardised data collection and integration across sites; supports long-term observation of ecosystem change	eLTER Europe (2023); DANUBIUS-RI (2024) https://elter-ri.eu/; https://www.danubius-ri.de/index.php.en
LifeWatch ERIC	e-Science infrastructure for biodiversity and ecosystem research	Ecological, data integration, socio-economic	Pan-European	Facilitates FAIR-by-design data interoperability and modelling for biodiversity and ecosystem-service assessments	LifeWatch ERIC (2024) https://www.lifewatch.eu
MAMBO - Modern Approaches to the Monitoring of BiOdiversity	Development and implementation of new tools for integrated biodiversity monitoring	Ecological, technological (AI, remote sensing), socio-economic, citizen science, governance	Pan-European	Develops integrated, cost-effective tools for harmonised biodiversity monitoring supporting EU policies.	MAMBO (2023) https://www.mambo-project.eu/

policy-driven projects is essential for establishing a continuous and harmonised monitoring architecture capable of supporting restoration efforts across scales. Embedding these integrated approaches into national and European reporting systems will enhance comparability, ensure long-term continuity and strengthen links between local restoration actions and EU-wide policy targets. Ultimately, such frameworks can transform monitoring from a technical exercise into a decision-support mechanism that sustains both biodiversity and the ecosystem services upon which societies depend. Integrated, adaptive

monitoring frameworks, linking ecological processes, ecosystem services and governance mechanisms, represent the foundation for effective, large-scale wetland restoration and long-term resilience across Europe.

Climate and hydrological drivers in riparian wetland monitoring

Building on the upstream-downstream focus perspective, we now turn our attention to a critical driver of riparian wetland and coastal system dynamics: climate and hydrological parameters. These parameters not only shape biodiversity and ecosystem functioning, but also underpin human well-being in communities that depend on wetland systems. Climate variables, such as air temperature, precipitation patterns, drought frequency and extreme weather events, exert a strong influence on wetland ecosystems and the species they support (Dudgeon 2019). At the same time, the relationship is bi-univocal: wetlands themselves regulate water storage, thermal exchange, greenhouse-gas fluxes and local micro-climates, thereby exerting feedback on local and even regional climate conditions (Hardouin et al. 2024). Thus, effective local-scale monitoring of these parameters is essential because regional averages often mask the fine-scale fluctuations that determine ecosystem resilience and the delivery of ecosystem services. Floodplains, for example, deliver critical services to human communities: flood regulation, water purification, carbon storage, fisheries and agricultural support and recreational and cultural values. When climate-driven regime shifts push a wetland system beyond a tipping point, local communities may lose vital protections, experience declines in fish stocks, face water scarcity or see reductions in cultural and recreational benefits (Barnard et al. 2021; Stammel et al. 2026; Wantzen et al. 2026). Restoration activities gain even greater urgency in this context: reconnecting floodplains, re-wetting drained soils, reinstating hydrological regimes and improving buffer zones are all efforts to increase ecosystem tolerance and delay or avoid threshold-crossing. Local monitoring thus supports not just ecological goals, but socio-ecological resilience.

According to the Intergovernmental Panel on Climate Change (IPCC), by 2081–2100, under high-emission scenarios such as SSP3-8.5, risks from weather extremes, droughts and intensified precipitation are projected to escalate significantly (IPCC 2021). In Europe, forecasts indicate long-term temperature increases between 1.9 °C and 6.1 °C relative to pre-industrial levels (Hielkema et al. 2023). Additional projections include increased consecutive dry days and more intense precipitation events. Understanding the long-term impact of these changes on biodiversity and ecosystem services remains complex, due to challenges in downscaling predictions to local and regional ecosystems (Weiskopf et al. 2020; Muluneh 2021). To understand potentially severe shifts in biodiversity and food-web functioning, it is essential to assess the status of climate adaptation in conserved areas and projects that apply nature-based solutions (NbS) (Pearce-Higgins et al. 2022; Schipper et al. 2024; Fink et al. 2026). Ecological impacts of climatic and meteorological drivers can be captured through bioclimatic and hydrological indicators — such as extreme heat-wave frequency, precipitation variability and habitat loss due to accelerating sea-level rise. When these indicators are combined with species vulnerability data (for example, species listed by the International Union for Conservation of Nature (IUCN) Red List) and species' upper-temperature tolerance limits (UTTL), mapped via species

Table 2. Key climate and hydrology variables for wetland monitoring to support ecosystem services and human well-being.

No	Variable	Description	Relevance to climate/hydrology and wetland/ community outcomes
1	Water-table / Groundwater depth (m)	Depth of the saturated zone beneath the surface	Indicates hydrological regime shifts affecting habitat, storage capacity and ecosystem services
2	Surface water level / Inundation duration	Number of days the wetland is flooded or ponded	Relates to flood regulation, habitat availability, species diversity and human flood risk
3	Precipitation (mm)	Seasonal totals, event intensity and dry-spell count	Drives inflows, drought stress and supports water-balance modelling for restoration and communities
4	Evapotranspiration / Evaporation rate (mm/day)	Rate of water loss via evaporation and vegetation	Affects water budget, carbon storage, vegetation health and service provision
5	Number of Consecutive Dry Days (CDD)	Days without measurable precipitation	Indicates drought vulnerability, vegetation and service decline and community water-scarcity risk
6	Maximum 5-day Precipitation (mm)	Highest rainfall amount over any 5-day period	Captures extreme-event risk: flood pulses, nutrient/sediment export, service disruption
7	Water Temperature (°C)	Surface or subsurface water temperature	Influences biological communities (fish/plants), biodiversity and ecosystem-service performance
8	Inflow & Outflow Volumes (m^3/day)	Volumes of water entering and leaving the wetland	Assesses connectivity, hydraulic residence time, service potential (purification, flood mitigation)
9	Soil Moisture Content (%)	Volumetric water content in wetland soils	Indicates root-zone health, vegetation stress, carbon release and service decline
10	Vegetation Phenology / Greenness Index (NDVI)	Remote-sensing measure of vegetation growth and condition	Serves as proxy for hydrology–vegetation link, community value (recreation, aesthetic) and ecosystem health

sensitivity distributions (SSD), meaningful trends and tipping-point risk-management insights emerge across marine, freshwater and terrestrial communities (Schipper et al. 2024). Multiple studies highlight the risk of climate-change-driven tipping points in riparian wetland and coastal systems: for example, coastal wetland habitat loss exceeding 50% could occur with just 0.25 m or less of sea-level rise, resulting in degraded biodiversity and ecosystem function (Alex et al. 2025; Ibáñez et al. 2026). These tipping points are critical because, once crossed, restoration efforts become much more difficult, much more expensive or even impossible to fully reverse (Alex et al. 2025). Restoration activities themselves are, therefore, linked with tipping-point management: by increasing ecosystem resilience through hydrological restoration, buffer enhancement, species re-introduction and connectivity improvement, we help delay or avoid threshold crossing, thereby preserving both nature and human well-being. Integrating these drivers into restoration planning and monitoring programmes enables restoration teams and decision-makers to detect emerging risks, calibrate interventions, measure outcomes relevant to both biodiversity and local communities and anticipate tipping-point conditions under future climate scenarios. Below is a table of key climate and hydrology variables recommended for wetland monitoring, with particular relevance for upstream and freshwater zones that sustain downstream floodplain ecosystem services and human communities (Noce et al. 2020; Naumann et al. 2021; IPCC 2022; SELINA Consortium 2024) (Table 2).

Innovative Monitoring for Riverine and Wetland Systems: Integrating Biodiversity, Ecosystem Services and Restoration Strategies under Climate Change

Recent technological innovations are reshaping the monitoring of biodiversity impacts in riparian wetland restoration programmes. Here, we provide a selective overview of emerging techniques and how they hold the potential to enhance tracking of habitat and species changes in restored systems.

A. Satellite-based remote sensing technologies provide an accessible entry point for large-scale monitoring of floodplain habitat mosaics where long-term biological surveys prove logistically difficult and costly (Jiménez López and Mulero-Pázmány 2019; Novković et al. 2024). Satellite platforms, such as the Sentinel-2 and Sentinel-1 (provided by the European Space Agency) enable large-scale, fine-resolution assessments of wetland condition and habitat classification, achieving accuracies above 85% (Huo and Niu 2024). The high temporal resolution and spectral diversity of Sentinel-2 data allow distinguishing amongst wetland habitat types, tracking seasonal and stress-related changes. Key spectral indices include the Normalised Difference Vegetation Index (NDVI; Rouse et al. (1974)) (a proxy for vegetation health and biomass) and the Normalised Difference Water Index (NDWI; McFeeters (1996)) (a measure of water presence and inundation extent) (Huo and Niu 2024; Farhadi et al. 2025). For example, flooded areas have been identified with up to ~ 98% accuracy in some studies (Farhadi et al. 2025). Cloud-based geospatial platforms, such as Google Earth Engine (Gorelick et al. 2017; GEE 2025), Sentinel EO Browser (Sinergise 2025) and the Copernicus Data Space Ecosystem (2023), permit large-scale imagery analysis and advanced processing including machine learning, without heavy local computational infrastructure. However, challenges remain in applying satellite-based monitoring: data gaps, frequent cloud cover, limited ground-truth validation and insufficient spatial resolution for very fine-scale habitat discrimination (Abdelmajeed et al. 2023; Williams et al. 2024).
B. Unmanned Aerial Vehicles (UAVs) complement satellite remote sensing by offering ultra-fine resolution imagery and detailed orthomosaics, enabling precise mapping of micro-habitats in riparian wetland systems (Cvijanović et al. 2025). UAV-derived surveys have assessed vegetation cover, species richness and community composition (Aznar et al. 2003; Rosset et al. 2013; Biggs et al. 2018; Kislik et al. 2020). When object-based image analysis (OBIA) and machine-learning algorithms are applied, UAV photogrammetry attains accuracy rates between 80% and 95% for classifying macrophyte taxa and functional groups (Cvijanović et al. 2025). UAVs are particularly effective in mapping floating and emergent vegetation, though submerged stands remain harder to detect in deeper or turbid waters (Chabot et al. 2016; Husson 2016; Benjamin et al. 2021). While UAVs provide high precision, their scalability is limited by personnel requirements, cost and time, so satellite plus UAV combinations often represent the best trade-off amongst cost, precision and temporal coverage (Farhadi et al. 2025).
C. Sensor networks, internet-of-things (IoT) systems and artificial intelligence (AI) now offer further advances in restoration-monitoring regimes. Accurate species identification is essential for wetland monitoring, yet it is often hindered by limited funding, scarce taxonomic expertise and the complexity of aquatic organism groups. The time lag between field sampling of aquatic macroinvertebrates, laboratory identification and the publication of results can extend over several years, making the information outdated by the time it becomes available (Jackson and Füreder 2006). Advanced AI-based methods, especially those utilising deep learning and convolutional neural networks (CNNs), provide automated and cost-effective alternatives

for species identification (Milošević et al. 2020; Milosavljević et al. 2021). A pioneering study by Simović et al. (2024) developed a database of 90 EPT taxa (mayflies, stoneflies and caddisflies) and trained a convolutional neural network to classify them with 98.7% overall accuracy. Summarily, this automated approach can accelerate the identification of macroinvertebrate species by up to 30 times compared to traditional methods (Jackson and Füreder 2006), while also ensuring standardisation. On the other hand, sensor networks deployed in floodplains, peatlands or coastal wetland restoration zones, such as water-level sensors, soil-moisture probes, connectivity/flow sensors and autonomous cameras or acoustic devices, can feed real-time data to cloud-based AI analytics. These systems may detect inundation frequency shifts, soil-moisture anomalies, habitat connectivity changes or species movements, enabling near-real-time adaptive management. Such integration of AI, sensor networks and cloud platforms is now recognised as a scalable and cost-effective approach to biodiversity and habitat monitoring (Sharma and Naik 2024; Santhosh 2025).

D. Environmental DNA (eDNA) metabarcoding involves sampling water, sediment or soil for trace genetic material, enabling detection of species presence or community composition without direct observation. This method is highly sensitive and increasingly cost-effective for freshwater biodiversity monitoring (Kurniawan et al. 2025; Yuan et al. 2025). For instance, eDNA metabarcoding has been shown to reveal fish community structure and detect invasive species more rapidly than conventional methods (He et al. 2024).
E. Citizen-science frameworks mobilise volunteers to collect ecological observations or sensor data across broad spatial and temporal scales, thereby enhancing monitoring coverage, engaging stakeholders and reducing costs (Turrini et al. 2018; von Gönner et al. 2024b). For example, community science platforms have been used to monitor river and wetland water levels and build large datasets of hydrological and biological observations (Turrini et al. 2018). Beyond data collection, citizen science can strengthen wetland literacy through hands-on learning, increase public acceptance of conservation and promote community stewardship (Kelly et al. 2019; von Gönner et al. 2024a). Recent freshwater initiatives demonstrate their value for assessing ecological status at scale: the FLOW project in Germany successfully applied standardised protocols aligned with the Water Framework Directive to evaluate macroinvertebrates, hydromorphology and pesticide pressures across small streams, with results closely matching professional monitoring (von Gönner et al. 2024a). Long-running initiatives such as FreshWaterWatch (Bishop et al. 2025) and the Angler's Riverfly Monitoring Initiative (Brooks et al. 2019) further illustrate the potential of trained volunteers to detect water-quality trends and biodiversity changes. Together, these examples show that citizen science can play a meaningful complementary role in monitoring and implementing the objectives of the Water Framework Directive, supporting adaptive management and enabling participatory restoration of streams and floodplains (Scoggins et al. 2022; Bischof et al. 2025).

The following table summarises selected technologies and example metrics that emerging monitoring systems bring to wetland restoration (Table 3).

Table 3. Emerging monitoring technologies and example metrics for wetland restoration programmes.

No	Technology	Example Metric	Potential Contribution to Monitoring
1	**UAV (drone)**	Vegetation functional-group coverage (floating, emergent, submerged)	Tracks habitat structure changes, monitors restoration progress at fine scale
2	**Satellite + AI/ML**	Automated change-detection rate (e.g. % change/year)	Detects early signs of habitat degradation or recovery, supports adaptive management
3	**Sensor network + AI**	Real-time inundation frequency/soil-moisture anomaly sensor	Monitors hydrology/connectivity changes, links to ecosystem service delivery
4	**eDNA sampling**	Species presence/absence from water/sediment sample	Rapid biodiversity assessment including cryptic or rare species
5	**Citizen science + mobile app**	Community-collected species occurrence or photo records	Enhances spatial/temporal data coverage, engages stakeholders and local communities

Towards integrated, standardised and future-ready Wetland Monitoring in Europe

Achieving standardised and effective monitoring of wetland ecosystems across Europe requires not only robust methods and harmonised standards, but also significant capacity in terms of skills, infrastructure and cross-border collaboration. However, considerable gaps remain — in particular between EU and non-EU countries — in the ability to implement advanced monitoring programmes, apply pan-European standards and harmonise across different legal monitoring obligations. Several EU funding schemes seek to bolster monitoring capacities within the emerging European Green Data Space (AD4GD Consortium 2023). Programmes such as Horizon Europe WIDERA ("Widening Participation and Spreading Excellence") (European Commission 2021) provide opportunities to address standardisation, methodological and management shortfalls in wetland biodiversity monitoring in non-EU countries. Meanwhile, Erasmus+ (European Commission 2021a) supports capacity building and standardisation through Strategic Partnerships and Knowledge Alliances. Over the past decade, several EU- and Member-State-funded initiatives have focused on river and wetland biodiversity monitoring, resulting in several information platforms capable of supporting standardised monitoring approaches (e.g. the Freshwater Platform and the European Environment Agency freshwater data portal). The European Topic Centre on Biodiversity and Ecosystems also addresses the status and trends of the EU freshwater environment and works to develop and support monitoring requirements and approaches in line with the EU Biodiversity Strategy 2030 (European Commission 2020) and climate change mitigation efforts. This landscape of funding instruments, platforms and monitoring initiatives provides a foundation on which more integrated, comparable and policy-relevant wetland monitoring systems can be built.

Wetlands across Europe, including floodplains, peatlands and coastal ecosystems, are increasingly exposed to synergistic pressures resulting from climate change, land-use intensification and incoherent policy frameworks (Schipper et al. 2024). The interplay of hydrological alterations, nutrient loading, infrastructure development and climatic extremes is accelerating wetland degradation and biodiversity loss. These cumulative impacts demonstrate that wetland decline is not driven by a single factor, but by systemic interactions between environmental, socio-economic and governance dimensions. Strengthening the resilience of wetland ecosystems, therefore, requires integrated approaches that address both ecological dynamics and institutional shortcomings. Incoherent or conflicting policies — such as agricultural subsidies promoting drainage or conversion, infra-

structure projects that alter hydrological connectivity and fragmented climate and biodiversity targets — undermine restoration efforts and reduce monitoring effectiveness. Overcoming these contradictions demands cross-sectoral policy alignment and the incorporation of wetland monitoring outcomes into decision-making at multiple governance levels. These pressures highlight why monitoring cannot remain fragmented: a future-ready system must detect the combined effects of climatic, hydrological, ecological and socio-economic drivers.

To achieve this, Europe needs comprehensive, harmonised and transnational monitoring frameworks capable of capturing the multi-dimensional interactions amongst climatic, hydrological, ecological and socio-economic drivers. Pan-European datasets and collaborative monitoring networks should guide managers and policy-makers in evidence-based decisions for biodiversity protection, restoration and Nature-based Solutions (NbS). A harmonised scientific monitoring system should integrate in-situ ecological observations, hydrological measurements and advanced remote sensing and modelling tools to enable data upscaling and comparability across regions. In parallel, developing targeted evaluation instruments is crucial for assessing the effectiveness and long-term sustainability of conservation and restoration measures. Citizen science can further enhance monitoring by broadening spatial and temporal coverage, fostering local ownership and increasing social acceptance of conservation actions. Technological innovations, such as AI-assisted mobile applications, citizen-science projects and open-access data platforms — exemplified by iNaturalist, FLOW and Restore4Life — have made public participation more accessible and scientifically useful (von Gönner et al. 2024a; Mason et al. 2025). When properly structured and validated, such initiatives can complement professional monitoring, especially for early warning and ecological assessment. Yet, scientifically validated methods and policy coherence remain fundamental. While large volumes of biological data are collected under the EU WFD and the Habitats and Birds Directives, the lack of integrated environmental, hydrological and socio-economic variables limits the capacity to distinguish natural variability from anthropogenic and policy-driven changes. Integrating biological, environmental and climatic datasets is, therefore, vital for revealing causal mechanisms, quantifying restoration success and providing information for adaptive management and policy evaluation. Moreover, embedding emerging technologies — such as AI-based species recognition, hyperspectral sensors and Earth Observation indicators — into monitoring frameworks can enhance accuracy, efficiency and cost-effectiveness (Moersberger et al. 2024; Lumbierres et al. 2025). These tools facilitate real-time feedback loops amongst monitoring, management and policy, enabling timely responses to ecological stress and socio-political challenges. Despite these advances, monitoring is still underfunded and institutionally fragmented, often treated as a secondary task when budgets are constrained. This lack of institutional prioritisation reflects a broader issue of policy incoherence, where monitoring responsibilities are dispersed across sectors with weak coordination and limited feedback into decision-making. In conclusion, long-term, integrated and well-funded monitoring must be recognised as a cornerstone of effective wetland restoration and governance. Strengthening methodological and policy frameworks that address the combined effects of climatic, anthropogenic and institutional drivers is essential for improving wetland resilience. Aligning future wetland monitoring with EU-wide adaptation, biodiversity and agricultural poli-

cies — and ensuring their mutual coherence — will be key to delivering measurable benefits for biodiversity, ecosystem services and human well-being.

River and floodplain restoration is increasingly conceptualised as a socio-economic investment model rather than solely an ecological intervention (Macháč et al. 2026). Within this framework, innovative monitoring plays a pivotal role by providing the empirical foundation to quantify ecosystem services, reduce investment risks and demonstrate long-term economic returns. Advanced monitoring technologies, such as sensor networks, remote sensing and AI-based data analytics, enable real-time assessment of hydrological dynamics, sediment processes and biodiversity outcomes. These data not only strengthen cost–benefit analyses (Barbier et al. 2011), but also enhance social legitimacy by fostering transparency, stakeholder participation and public trust (Turner et al. 2000). Moreover, robust monitoring systems stimulate technological innovation and market development, creating new opportunities in ecological data services and facilitating access to green finance, where measurable sustainability indicators are increasingly required (de Groot et al. 2010). Consequently, innovative monitoring should be regarded as a strategic investment that transforms wetland restoration into a credible, adaptive and economically viable pathway for climate resilience and sustainable regional development.

Rapid advances in artificial intelligence create a realistic pathway towards merging heterogeneous data streams into shared analytical environments where patterns can be discovered, gaps identified and predictions generated with unprecedented accuracy (Rafiq et al. 2025). The integration of community-generated knowledge with expert-driven monitoring and AI-supported analyses opens a mechanism through which local engagement generates effects that extend well beyond local scales. More importantly, it cultivates collective awareness and transforms individual contributions into a societal force capable of shaping how landscapes are understood, valued and managed.

The most effective integrative monitoring systems are expected to be those that combine technological innovation with climate-informed modelling and long-term ecological baselines. Bringing together remote sensing, UAV surveys, in situ sensors, molecular tools and citizen-generated observations within shared modelling frameworks will enable earlier detection of ecological change, clearer attribution of drivers and more reliable assessment of restoration outcomes. Such integration would also provide the informational backbone required for adaptive governance under the Nature Restoration Regulation and related European policy commitments and strengthen the evidence base for funding programmes that support large-scale restoration (Klusmann et al. 2026; Stoffers et al. 2026). Integrated monitoring is, therefore, both a technical and a societal investment, one that transforms individual and collective engagement into actionable knowledge for sustaining wetland ecosystems across the continent.

Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statement

No ethical statement was reported.

Use of AI

No use of AI was reported.

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Author contributions

Conceptualisation and overarching goals and aim of the manuscript were done by Dušanka Cvijanović. The first draft of the manuscript was written by all authors. All authors contributed to the writing, review and editing of the manuscript. Supervision was provided by all authors. All authors discussed the results and contributed to the final manuscript.

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Data availability

All of the data that support the findings of this study are available in the main text.

References

Abdelmajeed AYA, Albert-Saiz M, Rastogi A, Juszczak R (2023) Cloud-based remote sensing for wetland monitoring—A review. Remote Sensing 15(6): 1660. https://doi.org/10.3390/rs15061660

Åhlén I, Thorslund J, Hambäck P, Destouni G, Jarsjö J (2022) Wetland position in the landscape: Impact on water storage and flood buffering. Ecohydrology 15(7): e2458. https://doi.org/10.1002/eco.2458

Alex A, Saranya M, Sahoo C, Saini A (2025) Climate Change and Case Studies of Vulnerable Ecosystems and Wetlands. Eco-Resilience: Climate Change, Land Degradation and Sustainable Solutions. Springer Nature Switzerland, Cham, 97–126. https://doi.org/10.1007/978-3-032-00708-7_4

ALFAwetlands Consortium (2024) ALFAwetlands: European wetlands research and conservation initiative. https://alfawetlands.eu/alfawetlands-press-release-2024/

AD4GD [All Data 4 Green Deal] Consortium (2023) All Data 4 Green Deal – An integrated, FAIR approach for the Common European Data Space. https://ad4gd.eu/

Aznar JC, Dervieux A, Grillas P (2003) Association between aquatic vegetation and landscape indicators of human pressure. Wetlands 23(1): 149–160. https://doi.org/10.1672/0277-5212(2003)023[0149:ABAVAL]2.0.CO;2

Barbier EB, Hacker SD, Kennedy C, Koch EW, Stier AC, Silliman BR (2011) The value of estuarine and coastal ecosystem services. Ecological Monographs 81(2): 169–193. https://doi.org/10.1890/10-1510.1

Barnard PL, Dugan JE, Page HM, Wood NJ, Hart JAF, Cayan DR, Erikson L, Hubbard DM, Myers MR, Melack JM, Iacobellis SF (2021) Multiple climate change-driven tipping points for coastal systems. Scientific Reports 11: 94942. https://doi.org/10.1038/s41598-021-94942-7

Benjamin AR, Abd-Elrahman A, Gettys LA, Hochmair HH, Thayer K (2021) Monitoring the efficacy of crested floatingheart (Nymphoides cristata) management with object-based image analysis of UAS imagery. Remote Sensing 13(4): 830. https://doi.org/10.3390/rs13040830

Biggs HJ, Nikora VI, Gibbins CN, Fraser S, Green DR, Papadopoulos K, Hicks DM (2018) Coupling unmanned aerial vehicle (UAV) and hydraulic surveys to study the geometry and spatial distribution of aquatic macrophytes. Journal of Ecohydraulics 3(1): 45–58. https://doi.org/10.1080/24705357.2018.1466666

Biodiversa+ (2023) European Biodiversity Partnership – Biodiversa+. Biodiversa+ Monitoring & Governance Programme. https://www.biodiversa.eu/biodiversity-monitoring/governance/

Bischof R, Danker S, von Gönner J, Friedrichs-Manthey M, Tent L, Bonn A, Birk S (2025) Revitalizing small streams – A practical guide for community action. Zenodo. https://doi.org/10.5281/zenodo.15019119

Bishop I, Boldrini A, Clymans W, Hall C, Moorhouse H, Parkinson S, Scott-Somme K, Thornhill I, Loiselle S (2025) FreshWater Watch: Investigating the health of freshwater ecosystems, from the bottom up. Citizen Science: Theory and Practice 10: 2. https://doi.org/10.5334/cstp.754

Brooks SJ, Fitch B, Davy-Bowker J, Codesal SA (2019) Anglers' Riverfly Monitoring Initiative (ARMI): A UK-wide citizen science project for water quality assessment. Freshwater Science 38: 270–280. https://doi.org/10.1086/703397

Brunotte E, Dister E, Günther-Diringer D, Koenzen U, Mehl D (2009) Flussauen in Deutschland: Erfassung und Bewertung des Auenzustandes. BfN-Schriftenvertrieb im Landwirtschaftsverlag.

Burkhard B, Kroll F, Nedkov S, Müller F (2012) Mapping ecosystem service supply, demand and budgets. Ecological Indicators 21: 17–29. https://doi.org/10.1016/j.ecolind.2011.06.019

CBD (2022) Kunming-Montreal Global Biodiversity Framework. Decision adopted by the Conference of the Parties of the Convention on Biological Diversity CBD/COP/DEC/15/4, 19 December 2022. Convention on Biological Diversity, Montreal, Canada. https://www.cbd.int/conferences/2021-2022/cop-15/documents

Chabot D, Dillon C, Ahmed O, Shemrock A (2016) Object-based analysis of UAS imagery to map emergent and submerged invasive aquatic vegetation: A case study. Journal of Unmanned Vehicle Systems 5(1): 27–33. https://doi.org/10.1139/juvs-2016-0009

Copernicus Data Space Ecosystem (2023) Copernicus Data Space Ecosystem: Open access to Copernicus Sentinel data and cloud-based processing services. https://dataspace.copernicus.eu/

Council of Europe (1979) The Bern Convention – Convention on the Conservation of European Wildlife and Natural Habitats. Council of Europe, Bern, Switzerland. https://www.coe.int/en/web/bern-convention

European Commission (1992) Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora. Official Journal of the European Communities L206: 7–50. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A31992L0043

Council of the European Communities (2000) Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy. Official Journal of the European Communities L327: 1–72. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX-%3A32000L0060

European Commission (2009) Council Directive 2009/147/EC of 30 November 2009 on the conservation of wild birds. Official Journal of the European Union L20: 7–25. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32009L0147

Cvijanović D, Novković M, Milošević D, Stojković Piperac M, Galambos L, Čerba D, Stamenković O, Damnjanović B, Mesaroš M, Pavić D, Simić V, Trbojević I, Anđelković A, Drešković N, Stammel B, Cyffka B, Radulović S (2025) Conservation and ecological screening of small water bodies in temperate riverine wetlands using UAV photogrammetry (Middle Danube). Nature Conservation 58: 61–82. https://doi.org/10.3897/natureconservation.58.116663

DANUBIUS-RI (2024) International Centre for Advanced Studies on River–Sea Systems. https://www.danubius-ri.de/index.php.en

Davies CE, Moss D, Hill MO (2004) EUNIS habitat classification revised 2004. Report to the European Environment Agency – European Topic Centre on Nature Protection and Biodiversity, 127–143.

De Berry DA, Chamberlain SJ, Matthews JW (2015) Trends in floristic quality assessment for wetland evaluation. Bulletin - Society of Wetland Scientists (U.S.) 32(2): 12–22. https://doi.org/10.1672/UCRT083-281

de Groot RS, Alkemade R, Braat L, Hein L, Willemen L (2010) Challenges in integrating the concept of ecosystem services and values in landscape planning, management and decision making. Ecological Complexity 7(3): 260–272. https://doi.org/10.1016/j.ecocom.2009.10.006

del Tánago GM, Gurnell AM, Belletti B, García de Jalón D (2016) Indicators of river system hydromorphological character and dynamics: Understanding current conditions and guiding sustainable river management. Aquatic Sciences 78: 35–55. https://doi.org/10.1007/s00027-015-0429-0

Dudgeon D (2019) Multiple threats imperil freshwater biodiversity in the Anthropocene. Current Biology : CB 29(19): R960–R967. https://doi.org/10.1016/j.cub.2019.08.002

Dufour S, Piégay H (2009) From the myth of a lost paradise to targeted river restoration: Forget natural references and focus on human benefits. River Research and Applications 25(5): 568–581. https://doi.org/10.1002/rra.1239

Dziock F, Henle K, Foeckler F, Follner K, Scholz M (2006) Biological indicator systems in floodplains – a review. International Review of Hydrobiology 91(4): 271–291. https://doi.org/10.1002/iroh.200510885

eLTER Europe (2023) Integrated European Long-Term Ecosystem, critical zone and socio-ecological Research. https://elter-ri.eu/

England J, Angelopoulos N, Cooksley S, Dodd J, Gill A, Gilvear D, Johnson M, Naura M, O'Hare M, Tree A, Wheeldon J, Wilkes MA (2021) Best practices for monitoring and assessing the ecological response to river restoration. Water 13(23): 1–23. https://doi.org/10.3390/w13233352

Erős T, Kuehne L, Dolezsai A, Sommerwerk N, Wolter C (2019) A systematic review of assessment and conservation management in large floodplain rivers: Actions postponed. Ecological Indicators 98: 453–461. https://doi.org/10.1016/j.ecolind.2018.11.026

European Commission (2021) Horizon Europe – WIDERA: Widening Participation and Spreading Excellence. Framework Programme for Research and Innovation 2021–2027.

European Commission (2021a). Erasmus+ Programme Guide: Key Action 2 – Cooperation for innovation and the exchange of good practices. https://erasmus-plus.ec.europa.eu/knowledge-alliances

European Commission LIFE Programme (2024) LIFE Programme – EU funding for environment and climate action. https://cinea.ec.europa.eu/life_en

European Commission [EC] (2020) EU Biodiversity Strategy for 2030: Bringing nature back into our lives. European Commission, Brussels. https://environment.ec.europa.eu/strategy/biodiversity-strategy-2030_en

European Parliament and Council Regulation (EU) 2024/1991 of the European Parliament and of the Council of 24 June 2024 on nature restoration and amending Regulation (EU) 2022/869, Official Journal of the European Union, 2024, L 1991, 50 pp. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32024R1991

Farhadi H, Ebadi H, Kiani A, Asgary A (2025) Introducing a new index for flood mapping using Sentinel-2 imagery (SFMI). Computers & Geosciences 194: 105742. https://doi.org/10.1016/j.cageo.2024.105742

Fink S, Kräuchi N, Stofer S, Weber A, Horchler PJ (2026) Conservation planning for riverine biodiversity under changing climate: use of models. In: Kaden US, Schmid S, Wulf S, Marsden K, Klusmann C, Bonn A, Tockner K, Scholz M (Eds) Wetlands in a Changing Climate: Restoring Coasts and Floodplains. Nature Conservation 62: 47–62. https://doi.org/10.3897/natureconservation.62.149645

Fischer-Bedtke C, Fischer H, Mehl D, Podschun S, Pusch M, Stammel B, Scholz M [Eds] (2020) River Ecosystem Service Index (RESI) – Methoden zur Quantifizierung und Bewertung ausgewählter Ökosystemleistungen in Flüssen und Auen. UFZ-Bericht 2/2020.

Foeckler F, Diepolder U, Deichner O (1991) Water mollusc communities and bioindication of lower Salzach floodplain waters. Regulated Rivers 6(4): 301–312. https://doi.org/10.1002/rrr.3450060408

Gerisch M, Agostinelli V, Henle K, Dziock F (2012) More species, but all do the same: Contrasting effects of flood disturbance on ground beetle functional and species diversity. Oikos 121(4): 508–515. https://doi.org/10.1111/j.1600-0706.2011.19749.x

Gillson L, Dirk C, Gell P (2021) Using long-term data to inform a decision pathway for restoration of ecosystem resilience. Anthropocene 36: 100315. https://doi.org/10.1016/j.ancene.2021.100315

Globevnik L, Januschke K, Kail J, Snoj L, Manfrin A, Azlak M, Christiansen T, Birk S (2021) Preliminary assessment of river floodplain condition in Europe. ETC/ICM Technical Report 5/2020, European Topic Centre on Inland, Coastal and Marine Waters, 121 pp. https://www.eionet.europa.eu/etcs/etc-icm/products/etc-icm-reports/preliminary-assessment-of-river-floodplain-condition-in-europe

Google Earth Engine [GEE] (2025) Google Earth Engine: A planetary-scale platform for Earth science data & analysis. https://earthengine.google.com/

Gorelick N, Hancher M, Dixon M, Ilyushchenko S, Thau D, Moore R (2017) Google Earth Engine: Planetary-scale geospatial analysis for everyone. Remote Sensing of Environment 202: 18–27. https://doi.org/10.1016/j.rse.2017.06.031

Haase P, Bowler DE, Baker NJ, Bonada N, Domisch S, JR Marquez G, Heino J, Hering D, Jähnig SC, Schmidt-Kloiber A, Stubbington R, Altermatt F, Álvarez-Cabria M, Amatulli G, Angeler DG, Archambaud-Suard G, Jorrín IA, Aspin T, Azpiroz I, Bañares I, Ortiz JB, Bodin CL, Bonacina L, Bottarin R, Cañedo-Argüelles M, Csabai Z, Datry T, de Eyto E, Dohet A, Dörflinger G, Drohan E, Eikland KA, England J, Eriksen TE, Evtimova V, Feio MJ, Ferréol M, Floury M, Forcellini M, Forio MAE, Fornaroli R, Friberg N, Fruget J-F, Georgieva G, Goethals P, Graça MAS, Graf W, House A, Huttunen K-L, Jensen TC, Johnson RK, Jones JI, Kiesel J, Kuglerová L, Larrañaga A, Leitner P, L L'Hoste, Lizée M-H, Lorenz AW, Maire A, Arnaiz JAM, McKie BG, Millán A, Monteith D, Muotka T, Murphy JF, Ozolins D, Paavola R, Paril P, Peñas FJ, Pilotto F, Polášek M, Rasmussen JJ, Rubio M, Sánchez-Fernández D, Sandin L, Schäfer RB, Scotti A, Shen LQ, Skuja A, Stoll S, Straka M, Timm H, Tyufekchieva VG, Tziortzis I, Uzunov Y, van der Lee GH, Vannevel R, Varadinova E, Várbíró G, Velle G, Verdonschot PFM, Verdonschot RCM, Vidinova Y, Wiberg-Larsen P, Welti EAR (2023) The recovery of European freshwater biodiversity has come to a halt. Nature 620: 582–588. https://doi.org/10.1038/s41586-023-06400-1

Hardouin L, Decharme B, Colin J, Delire C (2024) Climate-driven projections of future global wetlands extent. Earth's Future 12(9): e2024EF004553. https://doi.org/10.1029/2024EF004553

He Y, Zhao X, Shi C, Peng K, Wang Z, Jiang Z (2024) Fish community monitoring in floodplain lakes: eDNA metabarcoding and traditional sampling revealed inconsistent fish community composition. Ecological Indicators 166: 112467. https://doi.org/10.1016/j.ecolind.2024.112467

Henle K, Scholz M, Dziock F, Stab S, Foeckler F (2006) Bioindication and functional response in floodplain systems: Where to from here? International Review of Hydrobiology 91(4): 380–387. https://doi.org/10.1002/iroh.200610891

Hielkema TW, Schipper CA, Gersonius B (2023) Global nature conservation and the apparent ineffective adaptation to climate pressures. Aquatic Ecosystem Health & Management 26: 33–46. https://doi.org/10.14321/aehm.026.02.033

Huo X, Niu Z (2024) Fine-resolution wetland mapping in the Yellow River Basin using Sentinel-1/2 data via zoning-based random forest with remote sensing feature preferences. Water 16(17): 2415. https://doi.org/10.3390/w16172415

Husson E (2016) Images from unmanned aircraft systems for surveying aquatic and riparian vegetation. Acta Universitatis Agriculturae Sueciae 115: 53. https://pub.epsilon.slu.se/id/document/13173278

Ibáñez C, Caiola N, Elphick CS, Grillas P (2026) To what extent is coastal wetland biodiversity endangered by climate change? How can we boost the resilience of coastal ecosystems? In: Kaden US, Schmid S, Wulf S, Marsden K, Klusmann C, Bonn A, Tockner K, Scholz M (Eds) Wetlands in a Changing Climate: Restoring Coasts and Floodplains. Nature Conservation 62: 63–94. https://doi.org/10.3897/natureconservation.62.154795

Ilg C, Dziock F, Foeckler F, Follner K, Gerisch M, Glaeser J, Rink, A, Schanowski A, Scholz, M, Henle K (2008) Long-term reactions of plants and macroinvertebrates to extreme floods in floodplain grasslands. Ecology 89(9): 2392–2398. https://doi.org/10.1890/08-0528.1

IPCC (2021) Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. In: Masson-Delmotte V, Zhai P, Pirani A, Connors SL, Péan C, Berger S, Caud N, Chen Y, Goldfarb L, Gomis MI, Huang M, Leitzell K, Lonnoy E, Matthews JBR, Maycock TK, Waterfield T, Yelekçi O, Yu R, Zhou B (Eds) Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. https://doi.org/10.1017/9781009157896

IPCC (2022) Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Pörtner H-O, Roberts DC, Tignor M, Poloczanska ES, Mintenbeck K, Alegría A, Craig M, Langsdorf S, Löschke S, Möller V, Okem A, Rama B (Eds) Cambridge University Press, Cambridge, UK and New York, NY, USA, 3056 pp. https://doi.org/10.1017/9781009325844

Jackson JK, Füreder L (2006) Long-term studies of freshwater macroinvertebrates: A review of the frequency, duration and ecological significance. Freshwater Biology 51(3): 591–603. https://doi.org/10.1111/j.1365-2427.2006.01503.x

Januschke K, Ledesma-Krist G, Scholz M, Gelhaus M, Stammel B, Hering D (2017) Metadaten – aktueller Bestand zum Monitoring in Auen. In: Schneider E, Werling M, Stammel B, Januschke K, Ledesma-Krist G, Scholz M, Egger G (Eds) Biodiversität der Flussauen Deutschlands. Naturschutz und Biologische Vielfalt 163: 25–40.

Januschke K, Hering D, Stammel B, Brunzel S, Scholz M, Rumm A, Foeckler F (2023) Biozönotische Erfolgskontrolle von Renaturierungsmaßnahmen an Gewässerufern und in Auen. Typologische Grundlagen und Bewertungsverfahren. BfN-Schriften 655. https://doi.org/10.1007/s35152-024-1865-8

Jiménez López J, Mulero-Pázmány M (2019) Drones for conservation in protected areas: Present and future. Drones 3(1): 10. https://doi.org/10.3390/drones3010010

Junk WJ, Bayley PB, Sparks RE (1989) The flood pulse concept in river floodplain systems. Canadian Special Publication of Fisheries and Aquatic Sciences 106: 110–127.

Kaden US, Scholz M, Buijse AD, Cvijanović D, Froese I, Diack I, Duffield S, Ibáñez C, Jähnig SC, Januschke K, Ludewig K, Marsden K, Müller P, Rodríguez-González PM, Schulz-Zunkel C, Stadler J, Stammel B, Wantzen KM, Weber A, Wulf S, Zak D, Bonn A (2023) Riverine and coastal wetlands in Europe for biodiversity and climate: State of knowledge, challenges and opportunities. BfN Discussion Paper, Bundesamt für Naturschutz, Bonn, Germany. https://doi.org/10.19217/hgr233en

Kaden US, Schmid S, Vieweg M, Scholz M, Dufour S (2026) European riverine and coastal wetlands under pressure: biodiversity and climate change. In: Kaden US, Schmid S, Wulf S, Marsden K, Klusmann C, Bonn A, Tockner K, Scholz M (Eds) Wetlands in a Changing Climate: Restoring Coasts and Floodplains. Nature Conservation 62: 13–45. https://doi.org/10.3897/natureconservation.62.163636

Kelly R, Fleming A, Pecl GT, Richter A, Bonn A (2019) Social license through citizen science: A tool for marine conservation. Ecology and Society 24: 16. https://doi.org/10.5751/ES-10704-240116

Khatik N (2022) Wetland monitoring programme and techniques. Environment and Ecology Research 10(2): 301–306. https://doi.org/10.13189/eer.2022.100220

Kislik C, Genzoli L, Lyons A, Kelly M (2020) Application of UAV imagery to detect and quantify submerged filamentous algae and rooted macrophytes in a non-wadeable river. Remote Sensing 12(20): 3332. https://doi.org/10.3390/rs12203332

Klusmann C, Brotherton P, Schiller T, Wulf S, Marsden K (2026) Wetlands in the EU policy context. In: Kaden US, Schmid S, Wulf S, Marsden K, Klusmann C, Bonn A, Tockner K, Scholz M (Eds) Wetlands in a Changing Climate: Restoring Coasts and Floodplains. Nature Conservation 62: 317–335. https://doi.org/10.3897/natureconservation.62.163780

Koenzen U (2005) Fluss- und Stromauen in Deutschland – Typologie und Leitbilder. Ergebnisse des F+E-Vorhabens „Typologie und Leitbildentwicklung für Flussauen in der Bundesrepublik Deutschland“ des Bundesamtes für Naturschutz. Angewandte Landschaftsökologie 65: 327. https://www.bfn.de/publikationen/broschuere/fluss-und-stromauen-deutschland-typologie-und-leitbilder

Koenzen U, Kurth A, Günther-Diringer D (2021) Status Report on Floodplains 2021 - Floodplains in Germany. Federal Agency for Nature Conservation (BfN) & The Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU), Bonn. https://doi.org/10.19217/brs211en

Kurniawan K, Wibowo A, Prakoso VA, Chadijah A, Astuti SS, Pratama BB, Nafiqoh N, Haryono H, Dahruddin H, Surbani IL, Jaya YYP, Sudarsono S, Rourke M, Baumgartner LJ, Stuart IG (2025) Utilizing environmental DNA metabarcoding and local ecological knowledge for fish biodiversity assessment in Rivers of Java, Indonesia. Knowledge and Management of Aquatic Ecosystems 426: 17.

Lang P, Schwab A, Stammel B, Ewald J, Kiehl K (2013) Long-term vegetation monitoring for different habitats in floodplains. Scientific Annals of the Danube Delta Institute 19: 39–48.

Lengyel S, Déri E, Varga Z, Horváth R, Tóthmérész B, Henry PY, Henle K (2008) Habitat monitoring in Europe: A description of current practices. Biodiversity and Conservation 17: 3327–3339. https://doi.org/10.1007/s10531-008-9395-3

LifeWatch ERIC (2024) LifeWatch ERIC – e-Science infrastructure for biodiversity and ecosystem research. https://www.lifewatch.eu/

Lumbierres M, Milanović M, Beja P, Bonn A, Breeze T, Brotons L, Fernández N, Herrando S, Jeliazkov A, Kissling WD (2025) Towards implementing workflows for essential biodiversity variables at a European scale. GECCO / Joint Research Centre. https://doi.org/10.1016/j.gecco.2025.e03699

Lumbierres M, Milanović M, Beja P, Bonn A, Breeze TD, Brotons L, Fernández N, Junker J, Liquete C, Solheim AL, Ordóñez AM, Moreira F, Santana J, Shinneman S, Smets B, Pereira HM, Valdez JW, van Grunsven RHA, Kissling WD (2025) Towards implementing workflows for essential biodiversity variables at a European scale. Global Ecology and Conservation 62: e03699. https://doi.org/10.1016/j.gecco.2025.e03699

MAMBO (2023) Modern Approaches to the Monitoring of BiOdiversity. https://www.mambo-project.eu/

Macháč J, Zaňková L, Hekrle M, Scholz M (2026) Nature-based solutions with sponge functions: socio-economic importance and valuation. In: Kaden US, Schmid S, Wulf S, Marsden K, Klusmann C, Bonn A, Tockner K, Scholz M (Eds) Wetlands in a Changing

Climate: Restoring Coasts and Floodplains. Nature Conservation 62: 289–315. https://doi.org/10.3897/natureconservation.62.164530

Mason BM, Mesaglio T, Barratt Heitmann J, Chandler M, Chowdhury S, Gorta SBZ, Grattarola F, Groom Q, Hitchcock C, Hoskins L, Lowe SK, Marquis M, Pernat N, Shirey V, Baasanmunkh S, Callaghan CT (2025) iNaturalist accelerates biodiversity research. BioScience 75(11): 953–965. https://doi.org/10.1093/biosci/biaf104

McFeeters SK (1996) The use of the Normalized Difference Water Index (NDWI) in the delineation of open water features. International Journal of Remote Sensing 17(7): 1425–1432. https://doi.org/10.1080/01431169608948714

Milosavljević A, Milošević Đ, Predić B (2021) Species identification for aquatic biomonitoring using deep residual CNN and transfer learning. Facta Universitatis, Series. Automatic Control and Robotics 20(1): 1–19. https://doi.org/10.22190/FUACR201118001M

Milošević D, Milosavljević A, Predić B, Medeiros AS, Savić-Zdravković D, Piperac MS, Leese F (2020) Application of deep learning in aquatic bioassessment: Towards automated identification of non-biting midges. The Science of the Total Environment 711: 135160. https://doi.org/10.1016/j.scitotenv.2019.135160

Moersberger H, Valdez J, Martin JGC, Junker J, Georgieva I, Bauer S, Beja P, Breeze TD, Fernández M, Fernández N, Brotons L, Jandt U, Bruelheide H, Kissling WD, Langer C, Liquete C, Lumbierres M, Solheim AL, Maes J, Morán-Ordóñez A, Moreira F, Pe'er G, Santana J, Shamoun-Baranes J, Smets B, Capinha C, McCallum I, Pereira HM, Bonn A (2024) Biodiversity monitoring in Europe: User and policy needs. Conservation Letters 17: e13038. https://doi.org/10.1111/conl.13038

Mohanty S, Pandey PC, Pandey M, Srivastava PK, Dwivedi CS (2024) Wetlands contribution and linkage to support SDGs, its indicators and targets-A critical review. Sustainable Development 32(5): 5348–5392. https://doi.org/10.1002/sd.2948

Müller M, Pander J, Stammel B, Gelhaus M (2016) Integrative Bewertung der Auswirkungen der Dynamisierung auf das Auenökosystem. In: Cyffka B, Binder F, Ewald J, Geist J, Gruppe A, Hemmer I, Zahner V (Eds) Neue dynamische Prozesse im Auenwald. Monitoring der Auenrenaturierung an der Donau zwischen Neuburg und Ingolstadt. Naturschutz und Biologische Vielfalt 150: 280–290.

Muluneh MG (2021) Impact of climate change on biodiversity and food security: A global perspective — a review article. Agriculture & Food Security 10: 36. https://doi.org/10.1186/s40066-021-00318-5

Naumann G, Cammalleri C, Mentaschi L, Feyen L (2021) Increased economic drought impacts in Europe with anthropogenic warming. Nature Climate Change 11: 485–491. https://doi.org/10.1038/s41558-021-01044-3

Noce S, Caporaso L, Santini M (2020) A new global dataset of bioclimatic indicators. Scientific Data 7: 398. https://doi.org/10.1038/s41597-020-00726-5

Novković M, Cvijanović DLj, Anđelković A, Mesaroš M, Drešković N, Radulović S (2024) Using UAV approach in monitoring of macrophytes and their habitats within small water bodies of pristine riparian wetlands: A case study of the Middle Danube Area (Serbia). Biologia Serbica 46(1): 48–66. https://doi.org/10.5281/zenodo.13929400

Ohnemus T, Zacharias S, Dirnböck T, Bäck J, Brack W, Forsius M, Mallast U, Nikolaidis NP, Peterseil J, Piscart C, Pando F, Poppe Terán C, Mirtl M (2024) The eLTER research infrastructure: Current design and coverage of environmental and socio-ecological gradients. Environmental and Sustainability Indicators 23: 100456. https://doi.org/10.1016/j.indic.2024.100456

Pearce-Higgins JW, Antão LH, Bates RE, Bowgen KM, Bradshaw CD, Duffield SJ, Franco AMA, Geschke J, Gregory RD, Harley MJ, Hodgson JA, Jenkins RLM, Kapos V, Maltby

KM, Watts O, Willis SG, Morecroft MD (2022) A framework for climate change adaptation indicators for the natural environment. Ecological Indicators 136: 108690. https://doi.org/10.1016/j.ecolind.2022.108690

Pereira HM, Cooper HD (2006) Towards the global monitoring of biodiversity change. Trends in Ecology & Evolution 21(3): 123–129. https://doi.org/10.1016/j.tree.2005.10.015

Perino A, Pereira H, Navarro L, Fernández N, Bullock J, Ceaușu S, Cortés-Avizanda A, van Klink R, Kuemmerle T, Lomba Â, Pe'er G, Plieninger T, Benayas J, Sandom C, Svenning JC, Wheeler H (2019) Rewilding complex ecosystems. Science 364: eaav5570. https://doi.org/10.1126/science.aav5570

Perino A, Pereira HM, Felipe-Lucia M, Kim H, Kühl HS, Marselle MR, Meya JN, Meyer C, Navarro LM, van Klink R, Albert G, Barratt CD, Bruelheide H, Cao Y, Chamoin A, Darbi M, Dornelas M, Eisenhauer N, Essl F, Farwig N, Förster J, Freyhof J, Geschke J, Gottschall F, Guerra C, Haase P, Hickler T, Jacob U, Kastner T, Korell L, Kühn I, Lehmann GUC, Lenzner B, Marques A, Motivans Švara E, Quintero LC, Pacheco A, Popp A, Rouet-Leduc J, Schnabel F, Siebert J, Staude IR, Trogisch S, Švara V, Svenning J-C, Pe'er G, Raab K, Rakosy D, Vandewalle M, Werner AS, Wirth C, Xu H, Yu D, Zinngrebe Y, Bonn A (2022) Biodiversity post-2020: Closing the gap between global targets and national-level implementation. Conservation Letters 15: e12848. https://doi.org/10.1111/conl.12848

Pusch M (2016) Auen-Quellen vielfältiger Dienstleistungen für den Menschen. Auenmagazin 9: 4–7.

Rafiq K, Beery S, Palmer MS, Harchaoui Z, Abrahms B (2025) Generative AI as a tool to accelerate the field of ecology. Nature Ecology & Evolution 9(3): 378–385. https://doi.org/10.1038/s41559-024-02623-1

Restore4Life Consortium (2024) Restoration of wetland complexes as life supporting systems in the Danube Basin (Restore4Life). https://restore4life.eu/

ReWET Consortium (2024) REstoration of WETlands to minimise emissions and maximise carbon uptake – a strategy for long term climate mitigation. https://www.re-wet-he.eu/

Rosset V, Simaika JP, Arthaud F, Bornette G, Vallod D, Samways MJ, Oertli B (2013) Comparative assessment of scoring methods to evaluate the conservation value of pond and small lake biodiversity. Aquatic Conservation 23(1): 23–36. https://doi.org/10.1002/aqc.2287

Rouillard J, Lago M, Abhold K, Röschel L, Kafyeke T, Mattheiß V, Klimmek H (2018) Protecting aquatic biodiversity in Europe: How much do EU environmental policies support ecosystem-based management? Ambio 47: 15–24. https://doi.org/10.1007/s13280-017-0928-4

Rouse JW, Haas RH, Schell JA, Deering DW (1974) Monitoring vegetation systems in the Great Plains with ERTS. NASA Special Publication SP-351: 309–317.

Santaoja M, Squires T, Klimkowska A, McGuinness S, Granath G, Törmänen T, Biedroń I, Terrisse A (2025) Best practices in European wetland restoration: A review of manuals and guidelines. Wetlands Ecology and Management 33: 10061. https://doi.org/10.1007/s11273-025-10061-4

Schipper CA, Hielkema TW, Ziemba A (2024) Impact of climate change on biodiversity and implications for nature-based solutions. Climate 12: 179. https://doi.org/10.3390/cli12110179

Santhosh B (2025) Integration of satellite data and AI for habitat monitoring and conservation. In AI and Machine Learning Techniques for Wildlife Conservation (pp. 267–296). IGI Global Scientific Publishing. https://doi.org/10.4018/979-8-3693-6935-7.ch011

Schipper CA, Hielkema TW, Ziemba A (2024) Impact of Climate Change on Biodiversity and Implications for Nature-Based Solutions. Climate 12(11): e179. https://doi.org/10.3390/cli12110179

Scholz M, Henle K, Dziock F, Stab S, Foeckler F [Eds] (2009) Entwicklung von Indikationssystemen am Beispiel der Elbaue. Naturschutz und Landschaftsplanung, Ulmer, Stuttgart, 482 pp.

Schulz-Zunkel C, Seele-Dilbat C, Anlanger C, Baborowski M, Bondar-Kunze E, Brauns M, Gapinski CM, Gründling R, von Haaren C, Hein T, Henle K, Junge FW, Kasperidus HD, Koll K, Kretz L, Rast G, Schnauder I, Scholz M, Schrenner H, Sendek A, Sprössig C, Tavares Nogueira C, Vieweg M, von Tümpling W, Weitere M, With C, Wunsch T, Dziock F (2022) Effective restoration measures in river-floodplain ecosystems: Lessons learned from the 'Wilde Mulde' project. International Review of Hydrobiology 107(1–2): 9–21. https://doi.org/10.1002/iroh.202102086

Scoggins M, Booth DB, Fletcher T, Fork M, Gonzalez A, Hale RL, Hawley RJ, Roy AH, Bilger EE, Bond N (2022) Community-powered urban stream restoration: A vision for sustainable and resilient urban ecosystems. Freshwater Science 41: 404–419. https://doi.org/10.1086/722638

SELINA Consortium (2024) Science for Evidence-based and Sustainable Decisions about Natural Capital (SELINA). https://project-selina.eu/

Sharma LK, Naik R (2024) Future Technologies for Wetland Studies. In Conservation of Saline Wetland Ecosystems: An Initiative towards UN Decade of Ecological Restoration (pp. 175-215). Singapore: Springer Nature Singapore. https://doi.org/10.1007/978-981-97-5069-6_6

Simović P, Milosavljević A, Stojanović K, Radenković M, Savić-Zdravković D, Predić B, Petrović A, Vuković M, Milošević D (2024) Automated identification of aquatic insects: A case study using deep learning and computer vision techniques. The Science of the Total Environment 935: 172877. https://doi.org/10.1016/j.scitotenv.2024.172877

Sinergise Laboratory for Geographical Information Systems Ltd (2025) Sentinel Hub EO Browser: A web platform for visualization and analysis of open-access satellite data. https://apps.sentinel-hub.com/eo-browser/

Staentzel C, Beisel JN, Gallet S, Hardion L, Barillier A, Combroux I (2018) A multiscale assessment protocol to quantify effects of restoration works on alluvial vegetation communities. Ecological Indicators 90: 643–652. https://doi.org/10.1016/j.ecolind.2018.03.050

Stammel B, Cyffka B, Geist J, Müller M, Pander J, Blasch G, Fischer P, Gruppe A, Haas F, Kilg M, Lang P, Schopf R, Schwab A, Utschik H, Weißbrod M (2012) Floodplain restoration on the Upper Danube (Germany) by re-establishing water and sediment dynamics: A scientific monitoring as part of the implementation. River Systems 20: 55–70. https://doi.org/10.1127/1868-5749/2011/020-0033

Stammel B, Stäps J, Schwab A, Kiehl K (2021) Are natural floods accelerators for streambank vegetation development in floodplain restoration? International Review of Hydrobiology 107: 76–87. https://doi.org/10.1002/iroh.202102091

Stammel B, Jähnig SC, Mehl D, Pusch M, Srđević Z, Tschikof M, Wulf S, Scholz M (2026) Assessing ecosystem services across scales to support nature-based solutions in river floodplains: a review of non-monetary tools. In: Kaden US, Schmid S, Wulf S, Marsden K, Klusmann C, Bonn A, Tockner K, Scholz M (Eds) Wetlands in a Changing Climate: Restoring Coasts and Floodplains. Nature Conservation 62: 95–119. https://doi.org/10.3897/natureconservation.62.148716

Stănica A, Tyler A, Scarrott R, Research Infrastructure Consortium (2025) DANUBIUS-RI, the International Centre for Advanced Studies on River–Sea Systems: An RI for the river–sea challenges of the 21st century. EGU General Assembly 2025, Vienna, Austria, April 2025. EGU25-11716. https://doi.org/10.5194/egusphere-egu25-11716

Stäps J, Gericke A, Lungu A, Stammel B [Eds] (2022) Ecosystem services in floodplains and their potential to improve water quality – a manual for the IDES Tool. Katholische Universität Eichstätt-Ingolstadt, Eichstätt, Berlin, Bukarest, 150 pp. https://doi.org/10.17904/ku.edoc.30670

Stoffers T, Schultze A-K, Ehlert T, Kaiser L, Scholz M, Nagelkerke LAJ (2026) Challenges and opportunities in restoring European free-flowing rivers. In: Kaden US, Schmid S, Wulf S, Marsden K, Klusmann C, Bonn A, Tockner K, Scholz M (Eds) Wetlands in a Changing Climate: Restoring Coasts and Floodplains. Nature Conservation 62: 355–381. https://doi.org/10.3897/natureconservation.62.173762

Thoms MC (2003) Floodplain–river ecosystems: Lateral connections and the implications of human interference. Geomorphology 56(3–4): 335–349. https://doi.org/10.1016/S0169-555X(03)00160-0

Tockner K, Malard F, Ward JV (2000) An extension of the flood pulse concept. Hydrological Processes 14: 2861–2883. https://doi.org/10.1111/conl.12771

Turner RK, van den Bergh JCJM, Söderqvist T, Barendregt A, van der Straaten J, Maltby E, van Ierland EC (2000) Ecological-economic analysis of wetlands: Scientific integration for management and policy. Ecological Economics 35(1): 7–23. https://doi.org/10.1016/S0921-8009(00)00164-6

Turrini T, Dörler D, Richter A, Heigl F, Bonn A (2018) The threefold potential of environmental citizen science: Generating knowledge, creating learning opportunities and enabling civic participation. Biological Conservation 225: 176–186. https://doi.org/10.1016/j.biocon.2018.03.024

van Rees CB, Waylen KA, Schmidt-Kloiber A, Thackeray SJ, Kalinkat G, Martens K, Domisch S, Lillebø AI, Hermoso V, Grossart H-P, Schinegger R, Decleer K, Adriaens T, Denys L, Jarić I, Janse JH, Monaghan MT, De Wever A, Geijzendorffer I, Adamescu MC, Jähnig SC (2020) Safeguarding freshwater life beyond 2020: Recommendations for the new global biodiversity framework from the European experience. Conservation Letters 14: e12771. https://doi.org/10.1111/conl.12771

von Gönner J, Gröning J, Grescho V, Neuer L, Gottfried B, Hänsch VG, Molsberger-Lange E, Wilharm E, Liess M, Bonn A (2024a) Citizen science shows that small agricultural streams in Germany are in a poor ecological status. The Science of the Total Environment 171183. https://doi.org/10.1016/j.scitotenv.2024.171183

von Gönner J, Masson T, Köhler S, Fritsche I, Bonn A (2024b) Citizen science promotes knowledge, skills and collective action to monitor and protect freshwater streams. People and Nature 6: 2357–2373. https://doi.org/10.1002/pan3.10714

Wantzen KM, Cao Y (2026) Cultural practices in European riverine floodplains: formation, typology, co-decline of biocultural diversity, and emerging drivers of conservation and sustainable management. In: Kaden US, Schmid S, Wulf S, Marsden K, Klusmann C, Bonn A, Tockner K, Scholz M (Eds) Wetlands in a Changing Climate: Restoring Coasts and Floodplains. Nature Conservation 62: 195–215. https://doi.org/10.3897/natureconservation.62.156771

Weiers S, Bock M, Wissen M, Rossner G (2004) Mapping and indicator approaches for the assessment of habitats at different scales using remote sensing and GIS methods. Landscape and Urban Planning 67(1–4): 43–65. https://doi.org/10.1016/S0169-2046(03)00028-4

Weiskopf SR, Rubenstein MA, Crozier LG, Gaichas S, Griffis R, Halofsky JE, Hyde KJ, Morelli TL, Morisette JT, Muñoz RC (2020) Climate change effects on biodiversity, ecosystems, ecosystem services, and natural resource management in the United States. The Science of the Total Environment 733: 137782. https://doi.org/10.1016/j.scitotenv.2020.137782

Wenskus F, Hecht C, Hering D, Januschke K, Rieland G, Rumm A, Scholz M, Weber A, Horchler P (2025) Effects of floodplain decoupling on taxonomic and functional diversity of terrestrial floodplain organisms. Ecological Indicators 170: 113106. https://doi.org/10.1016/j.ecolind.2025.113106

Williams KJ, Ferrier S, Lehmann EA, Harwood TD, Donohue RJ, Giljohann KM, Valavi R, Liu N, Ware C, Lyon P, Van Niel TG, McVicar TR, Richards A, Malley C (2024) Overcoming key challenges of satellite-based monitoring of ecosystem condition: A continental-scale example from Australia. https://doi.org/10.32942/X2333Q

Yuan H, Han J, Yang M, Chen S, Pang X (2025) DNA Metabarcoding: Current Applications and Challenges. Journal of Agricultural and Food Chemistry 73(33): 20616–20632. https://doi.org/10.1021/acs.jafc.5c06002

Zacharias I, Liakou P, Biliani IA (2020) Review of the status of surface European waters twenty years after WFD introduction. Environmental Processes 7: 1023–1039. https://doi.org/10.1007/s40710-020-00458-z

Zscheischler J, Westra S, van den Hurk BJJM, Seneviratne SI, Ward PJ, Pitman A, AghaKouchak A, Bresch DN, Leonard M, Wahl T, Zhang X, Steffen W, Sillmann J (2018) Future climate risk from compound events. Nature Climate Change 8: 469–477. https://doi.org/10.1038/s41558-018-0156-3